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Generators for piezoelectric motors

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Abstract. The principle of ultrasonic motors is described in this paper and different types are presented with their own specific electrical excitations. Some generators are proposed which provide four-output sine or square wave signals. Their frequency and amplitude may be adjusted over a large operating range.

1. Introduction

Piezoelectric motors are put into motion through ultrasonic vibrations. The stator of the ultrasonic motor is made of piezoelectric ceramic which can be free or coupled to a metallic part. Under the effects of electrical excitation, the stator is bent and the rotor, pressed onto the stator surface, is forced to rotate through the frictional force between them.

These motors are interesting for applications where low speed with high torque and very low response times are required. Many kinds of ultrasonic motor have been proposed in the literature. This paper deals with the operating principle of ultrasonic motors and different types are presented. It is shown that specific electrical excitations are necessary. Some power supplies built in our laboratory are described.

2. Operating principle of ultrasonic motors

In order to make a motor rotate, an elliptic movement must be created at the rotor–piezoelectric stator interface [1]. In this case, the rotor is pressed onto the stator surface and is put into motion by frictional forces at the interface: the tangential component acts as a driving force and the normal component controls the frictional forces (figure 1).

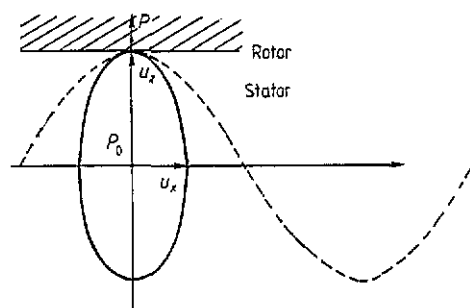


Figure 1. Elliptic movement at the rotor–stator interface.

Speed and direction of rotation can be modified by changing the phase shift between the components U_x and U_z . According to this principle many kinds of motor, both linear and rotative, have been built.

3. Classification of ultrasonic motors

Classifying such motors into groups is based upon the realization of the elliptic motion of displacements. In this paper three groups are distinguished.

3.1. Ultrasonic multi-mode motors

These motors use two different vibrations which are independently excited by two piezoelectric elements. Several vibration modes can be used.

3.1.1. Thickness–shearing modes. Two piezoelectric transducers—one vibrating along its thickness mode and the other one along its shearing mode at the same frequency—are coupled mechanically. Both vibrators must be excited in quadrature. This yields an elliptic motion at the surface. A generator providing two outputs in quadrature is required (figure 2(a)).

3.1.2. Longitudinal–torsional modes. The two components are a torsional vibrator—ceramics are polarized along the circumferential direction—and a longitudinal vibrator. Two possibilities may apply:

- (i) The longitudinal vibrator can be stimulated out of its resonance frequency, with an actuator for example. So, only a single output generator is necessary.
- (ii) Alternatively, longitudinal and torsional resonators can be chosen in order to work at the same resonance frequency. In the latter case, a generator providing two outputs in quadrature is needed (figure 2(b)).

3.1.3. Orthogonal–longitudinal modes. Two longitudinal vibrators are assembled orthogonally. They must be excited with a 90° phase angle (figure 2(c)).

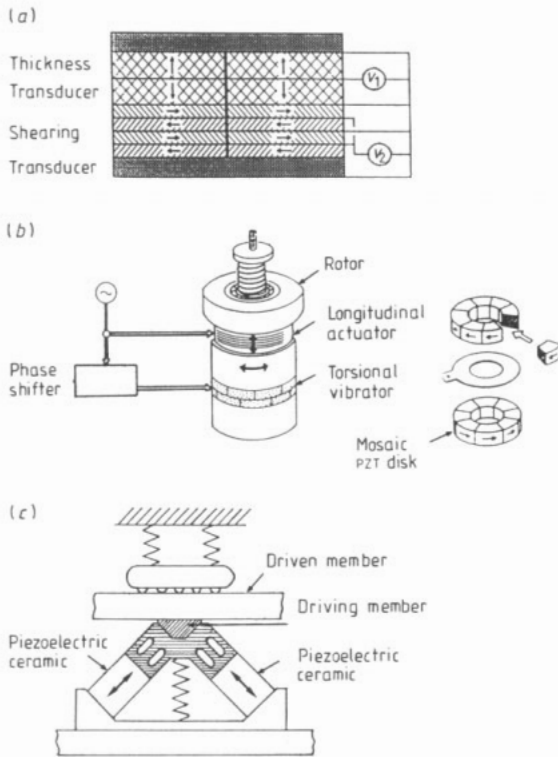


Figure 2. Principle of motors using: (a) thickness and shearing modes (stator only) [2]; (b) longitudinal and torsional modes [3]; (c) two orthogonal longitudinal vibrations [4].

3.2. Mode conversion ultrasonic motors

These motors use a mode conversion to obtain two vibration modes with a single piezoelectric element. Several devices can be found. In figure 3, the longitudinal vibration excites a flexion mode in the coupler which is converted into a torsion mode in the beam. The rotor, pressed onto the beam surface, is then put into motion. Unfortunately, only one sense of rotation is available.

3.3. Travelling wave ultrasonic motor [6]

It seems that this solution is the most interesting one at present because of its maximum simplicity—efficiency compromise. First, we show how a travelling wave

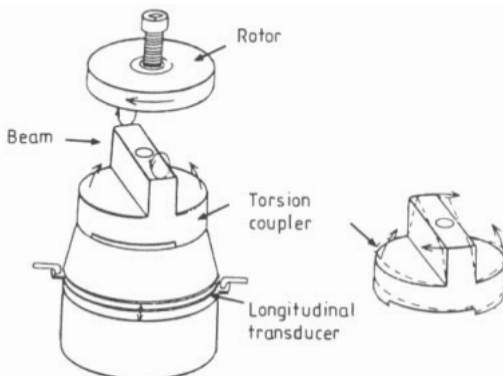


Figure 3. Mode conversion ultrasonic motor [5].

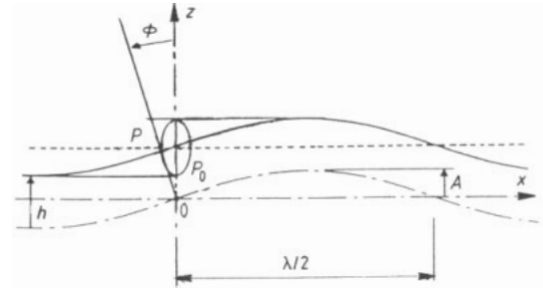


Figure 4. Elliptic motion of a point on the stator surface.

generates a particular elliptic movement. Then, two different travelling wave motors are presented.

3.3.1. Operating principle (figure 4). Let us consider a bar of thickness h which is bent longitudinally under the effects of a travelling wave generated by piezoelectric ceramics.

w is the amplitude of the wave along the Oz axis:

$$w(x, t) = A \sin(\omega t - kx)$$

The point P_0 moves to P due to the travelling wave. If ϕ is the angle made by OP and the Oz axis or OP_0 , the P coordinates are:

$$z_P = A \sin(\omega t - kx) - h(1 - \cos \phi)$$

$$\simeq A \sin(\omega t - kx) \quad \text{because } \phi \text{ is small}$$

$$x_P = -OP \sin \phi = -h \sin \phi$$

$$\tan \phi = \frac{dz_P}{dx} \approx \sin \phi$$

$$x_P = -\frac{dz_P}{dx} = kAh \cos(\omega t - kx).$$

$$\text{So } \left(\frac{x_P}{kAh}\right)^2 + \left(\frac{z_P}{A}\right)^2 = 1.$$

The point P on the stator surface draws an elliptical trajectory. A rotor pressed onto the stator surface is put into motion by the tangential velocity along the Ox axis.

It is then understood that this movement can be realized by a travelling wave—and an ultrasonic motor whose operating mode is based upon this elliptical motion can then be built.

The easiest way to provide a progressive wave is to generate and sum two standing waves correctly phase shifted in time and space.

The general form of a standing wave is:

$$s_1 = A \sin(\omega t - kx) + A \sin(\omega t + kx) = 2A \sin \omega t \cos kx.$$

Moreover, it is easy to generate another standing wave shifted in space by $\lambda/4$ and in time by $\pi/2$ with respect to the first one.

$$\begin{aligned} s_2 &= A \sin \left[\left(\omega t - \frac{\pi}{2} \right) - k \left(x + \frac{\lambda}{4} \right) \right] \\ &\quad + A \sin \left[\left(\omega t - \frac{\pi}{2} \right) + k \left(x + \frac{\lambda}{4} \right) \right] \\ &= -2A \cos \omega t \sin kx \quad \text{with } k = \frac{2\pi}{\lambda}. \end{aligned}$$

The resulting wave is a progressive one:

$$s = s_1 + s_2 = 2A \sin(\omega t - kx).$$

As a conclusion, it is possible to get a travelling wave from two standing waves correctly dephased in time and space and to use it to make a motor rotate. Piezoceramics are used in order to provide progressive waves.

3.3.2. Progressive waves generated on the cylindrical surface of a disc or a ring. Let us consider a piezoelectric ring, radially polarized and excited at different resonance frequencies in extensional mode.

At any particular point, two displacements are observed:

- (i) radial: $u_1(\theta, t) = A \cos n\theta \cos \omega t$;
- (ii) tangential, generated by the radial excitation:

$$w_1(\theta, t) = -nA \sin n\theta \cos \omega t.$$

n corresponds to the different excited resonance frequencies.

The movement of the considered point is not elliptic:

$$\left(\frac{u_1}{A}\right)^2 + \left(\frac{w_1}{nA}\right)^2 = \cos^2 \omega t \neq 1.$$

To generate the particular elliptic movement, a new wave must be provided. The disc or the ring must therefore be sectorized and excited with electric signals correctly dephased as shown in figure 5 for $n = 1$.

The new excitation yields radial and tangential displacements whose amplitudes are given by:

$$\begin{aligned} u_2 &= A \cos\left(n\theta - \frac{\pi}{2}\right) \cos\left(\omega t - \frac{\pi}{2}\right) \\ &= A \sin n\theta \sin \omega t \\ w_2 &= -nA \sin\left(n\theta - \frac{\pi}{2}\right) \cos\left(\omega t - \frac{\pi}{2}\right) \\ &= nA \cos n\theta \sin \omega t. \end{aligned}$$

The displacements are:

$$\begin{aligned} u &= u_1 + u_2 = A \cos(\omega t - n\theta) \\ w &= w_1 + w_2 = nA \sin(\omega t - n\theta). \end{aligned}$$

The resulting movement is then elliptic: $(u/A)^2 + (w/nA)^2 = 1$. In order to obtain this result, electrodes covering an angle of $\pi/2n$ must be made on the ceramic and these sectors must then be excited with signals in quadrature. So it is necessary to have a generator with four outputs regularly dephased by $\pi/2$.

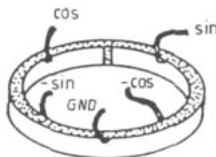


Figure 5. Ceramic excitations to create a progressive wave [7].

Two outputs in quadrature can be sufficient if the polarizations of the different sectors have been made alternately in one direction and then in the opposite.

3.3.3. Progressive waves generated on the plane surface of a ring. Bending vibrations are used along the thickness of a ring polarized along the thickness, mechanically coupled to an elastic solid.

An example is Shinsei's solution given in figure 6(a). For the same reasons as before, there are two kinds of sector: $\lambda/2$ wide, alternately polarized in one direction and then in the opposite one and dephased by $\lambda/4$ in space. Both half rings are excited by signals in quadrature (one in cosinus and the other in sinus). The other sectors— $\lambda/4$ and $3\lambda/4$ wide—are not excited to create a $\lambda/4$ space shift.

Other versions exist. An example is shown in figure 6(b): all sectors are excited and their polarization is uniform. A four-output generator must then be used.

4. Specifications for electrical generators

The most interesting motors have been presented. It has been seen that specific generators are necessary as follows.

- (i) Two outputs in quadrature are essential. Four outputs would be useful if it is not possible to get alternate polarizations. At present, it is interesting for development and adjustment to have a great number of variable parameters.
- (ii) Voltage amplitude applied to the piezoceramics must be adjustable.
- (iii) Many kinds of motor are tested and it is indispensable for each of them to research their resonance frequency and to control it if changes due to heating, for example, occur. An adjustable frequency generator is therefore essential.

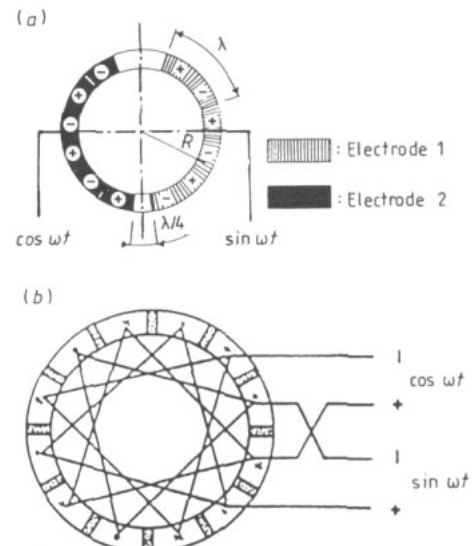


Figure 6. Stator ceramics for progressive wave motor: (a) Shinsei's structure; (b) continuous sectorization [8].

- (iv) It is also important to determine the appropriate parameters which allow a good speed variation: voltage, frequency or phase shift between the different outputs.

A generator providing all of these adjustments would be interesting. With these specifications, three generators with four dephased outputs have been designed and built in our laboratory. With the two first ones, a great number of parameters may be adjusted. The third one is a minimal version. The specifications of these models are described below.

5. Electrical generators

5.1. Sine wave generator

This provides four output sine signals $e_1, e_2, -e_1, -e_2$ whose frequency may be adjusted from 10 kHz to 100 kHz. Moreover its amplitude may vary up to 50 V_{RMS} with a maximum output current reaching 1 A. The principle is shown in figure 7.

5.1.1. Principle. The outputs are driven through a microprocessor-controlled device and the different parameters are computed through a keyboard and displayed on an LCD panel.

Each double output channel may supply an 1 A current under a 100 V_{RMS} voltage if series coupling is chosen or 2 A under 50 V_{RMS} if parallel coupling is used.

Two functioning modes are to be distinguished:

- (i) both ways provide signals having the same frequency but dephased (the phase shift $\Delta\phi$ may be adjusted from 0 to 180°);
- (ii) both ways provide entirely independent signals (in frequency and amplitude).

This functioning mode may be used for vibration coupled motors.

Figure 7 shows two almost identical outputs. However a few differences may be observed.

- (i) Output 1. The frequency synthesizer (PLL-1) and the controlled gain amplifier (CGA) are driven by a microprocessor card. The power amplifier has a constant gain.
- (ii) Output 2. The phase locked loop (PLL-2) may be used either as a frequency synthesizer (both channels are independent) or as a phase shifter. In the latter case, the power amplifier output signals are transferred to the PLL-2 after having been converted into analogue signals and the phase shift value $\Delta\phi$ is also sent to the PLL-2 by the microprocessor.

5.1.2. Description of the different modules. The different components are now described.

- (i) *The phase locked loop*

The programmable bit rate generator (MC 14411 from Motorola) divides the 4 MHz quartz frequency to obtain a reference logical signal used by the PLL (MC 145155 from Motorola) whose 14-bit feedback divider is of a serial loading type. The output signal after a low pass filtering will be used to activate a voltage-controlled oscillator (ICL 8038) supplying sine and square wave output signals ranging up to 100 kHz. Moreover a digital to analogue converter (DAC) (AD 7523) generates the DC voltage required by the phase shift in the PLL-2.

- (ii) *The CGA module.*

The VCO sine output signals reach 6 V_{pp} and constitute the input signals for the CGA cards.

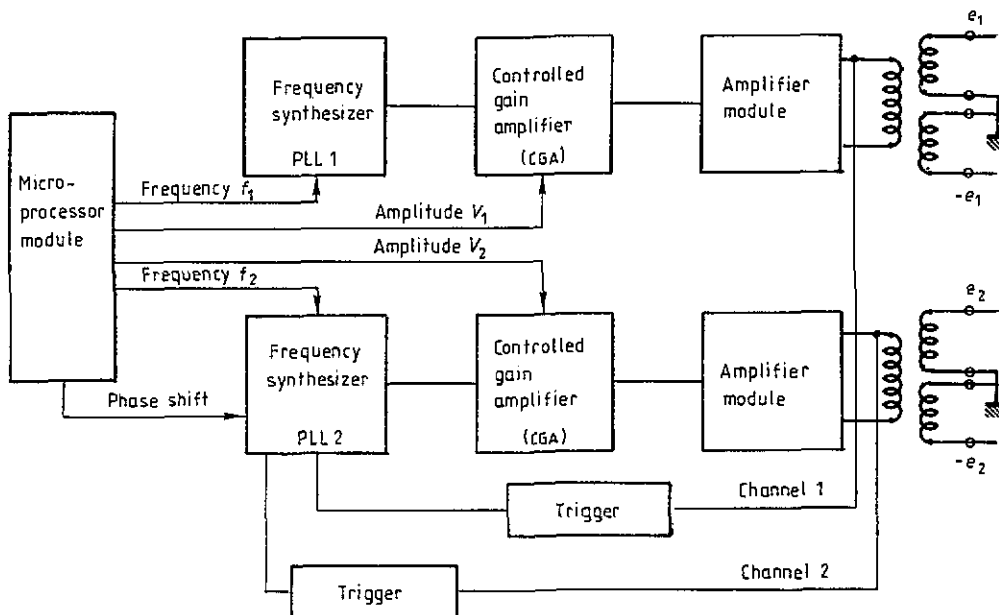


Figure 7. Principle scheme. Output transformers are represented in the four-sector mode.

However, the amplitude of those signals may be computed and then controlled by the microprocessor board. This CGA module is based upon a DAC (AD 7523) which switches $R/2R$ resistors. These resistors may be of different values depending on the binary word at the input of the converter.

(iii) *Amplifier module.*

This part of the generator is based upon a push-pull amplifier whose outputs are achieved through a twin primary coil ferrite transformer. These coils are bridge connected when only a single power supply is required (figure 8).

The primary of the transformer which is powered by a $33\text{ V}_{\text{RMS}}-3\text{ A}_{\text{RMS}}$ source induces simultaneously a $50\text{ V}_{\text{RMS}}-1\text{ A}_{\text{RMS}}$ signal in each secondary. The MOS transistors IRF 450 (Hexfet N Canal) (M1, M2) used in this application are characterized by a very small $R_{\text{DS(on)}}$ resistor ($R_{\text{DS(on)}} = 0.4\ \Omega$ with $i = 14\text{ A}$) and a very large transconductance (14 A V^{-1}), allowing the use of a low-power command.

Switching times are also very small ($t_{\text{on}} = 27\text{ ns}$ maximum, $t_{\text{off}} = 150\text{ ns}$ maximum).

These power amplifiers are current limited by using thermal protections on the transistors (achieved by CTN resistors). The amplifier gain reaches 14.

A $100\text{ V}_{\text{RMS}}$ output voltage can be then obtained while the amplifier module is powered by a 6.6 V_{pp} input voltage.

(iv) *Microprocessor module.*

This card uses an MC 6809 microprocessor and controls a number of devices: keyboard, LCD panel, PLLs, DACs driving the PLLs and CGA modules.

5.2. The square wave generator

This provides four square output waves: $e_1, -e_1, e_2, -e_2$ whose frequency can be adjusted between 20 kHz and 200 kHz. The amplitude of these signals can vary from 0 to $200\text{ V}_{\text{RMS}}$ with a maximum output current reaching 1 A.

5.2.1. Principle. The principle scheme (figure 9) shows the motor rotation speed adjustment device which can be achieved by amplitude, frequency or phase shift variation.

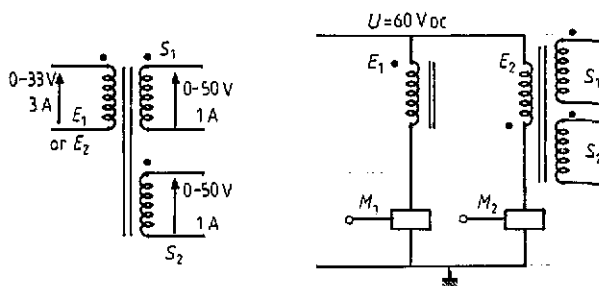


Figure 8. Output ferrite transformer for a single channel.

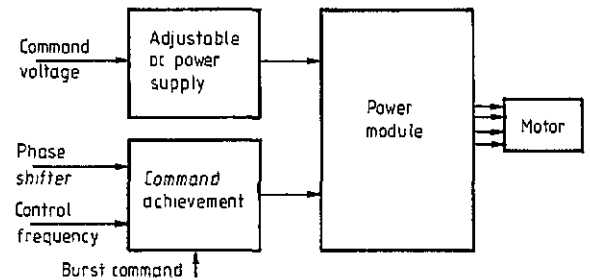


Figure 9. Principle scheme.

The functioning principle is based upon a power switching module which requires an adjustable DC power supply according to a command achievement module.

5.2.2. Description of the different modules. The modules of the square wave generator are now described.

(i) *Power module.*

Each sector of the piezoelectric ceramic must be powered by square waves $+E$ and $-E$ which are obtained from the DC voltage switching. The chopper used here is of a capacitive half bridge type (figure 10).

This structure allows one to put one of the faces of the piezoelectric stator to a referenced potential which is an evident advantage on a device using four switches. However, a DC voltage whose amplitude is $2E$ must be generated.

The maximal switching frequency (200 kHz) required makes it necessary to choose fast switchers (MOSFET type IRF 840 transistors from Motorola).

It is noticeable that the command voltage V_{GS} is made independent of the drain current which flows through the piezoceramic. For the bipolar transistors, the base current driving the switching transistor depends on the load in the collector. In that application, the load corresponds to the impedance of the ceramic and depends strongly on the frequency.

For instance, if the current in the base is too high, it would yield a higher saturation of the transistor and then an increase of the blocking time.

The generator is built in order to drive four dephased sectors. The electrical scheme shown in figure 8 must then be reproduced four times.

(ii) *Adjustable DC power supply (figure 11).*

This voltage can be obtained from the mains and a booster transformer (whose ratio must be greater than

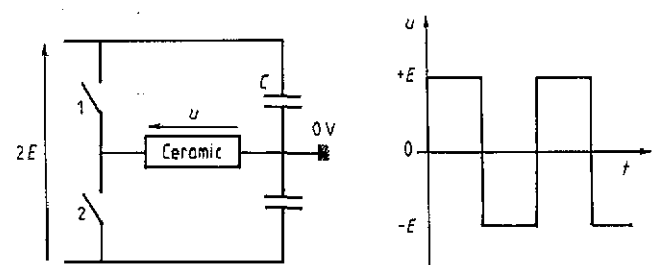


Figure 10. The capacitive half-bridge type converter.

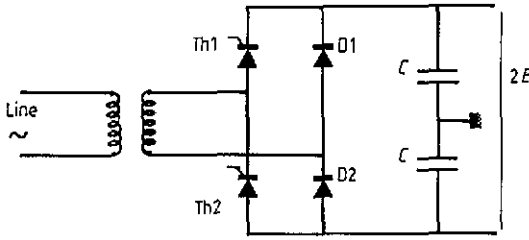


Figure 11. Adjustable DC power supply.

unity). The use of a dual-rectifier (diode-thyristor) mono-phase compound bridge yields the adjustment of the power supply value. Both thyristors are driven in anti-phase through the pulse transformer working as a galvanic isolator at the same time. The voltage adjustment is achieved by an Arccos command of the thyristors' firing angle.

(iii) Command achievement.

This module must supply dephased signals to control the four ceramic sectors. The IC XR 2206 can deliver a triangular wave whose frequency ranges from 20 to 200 kHz. A Schmidt trigger made with an operational amplifier LM 319 is therefore used to make a square wave work as a reference.

The dephased signal is obtained by using comparators and RS latches. This can be achieved by inverting the signal from the VCO and by comparing it with an adjustable voltage as shown in figure 12.

The phase shifter can then provide a signal with the same duty cycle (0.5) as the reference signal and dephased from $-\pi/2$ to $\pi/2$. Both the speed and sense of rotation can vary.

The control signals of the four outputs, which are in antiphase by pairs, can be obtained by the use of a logical inverter. The conduction of both MOSFET transistors must be absolutely avoided at the same time. This can be done by using the small circuitry described in figure 13. This module is located each way for the transistor control.

In practice, in order to drive the IRF 840 transistors, it is necessary:

- (i) to get a logical high level to open the first switch and
- (ii) to get a logical low level to close the other switch.

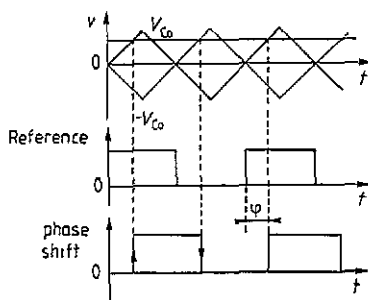


Figure 12. Phase shifter working principle.

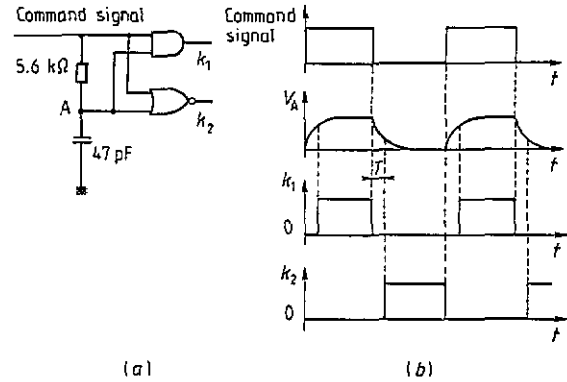


Figure 13. MOSFET transistors trigger circuitry (a) and chronograms (b).

v_1 and v_2 driving signals must therefore be inverted. This can be done with two input NAND gates. The second input works as an inverter and it is used for functioning default processing such as higher output current detection. Moreover this input can be used when the piezoelectric motor works in a discontinued mode (bursts). The control signal can be provided by an external low-frequency generator.

5.3. Autonomous generator

This provides four output square wave signals in quadrature. Their frequency can range from 30 kHz to 70 kHz. The amplitude of these signals can vary from 10 V_{RMS} to 45 V_{RMS} , supplying at the same time a 0.15 A current (figure 14).

5.3.1. Description of each module. A brief description of each module constituting this generator is given in this section.

(i) The phase shifter.

Four signals in quadrature are required by the four switches of the power module. Signals are provided by a voltage-controlled oscillator whose frequency is twice the required frequency to drive the motor. Finally after being transformed into logical signals, across JK flip-flops and gates, these signals are obtained and a 1 μs delay time between them must be present in order to avoid problems such as encroachment phenomena as seen before.

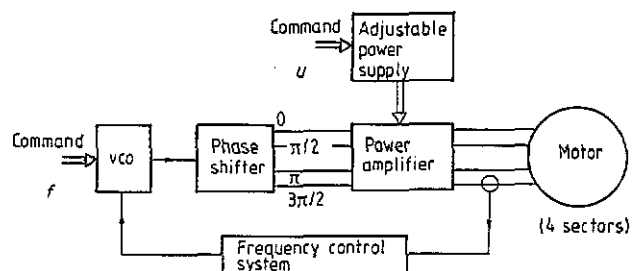


Figure 14. Autonomous generator principle.

(ii) *Power amplifier.*

The electric circuitry which has been designed is of a push-pull type. It uses two transistors and a twin secondary middle point transformer. This limits the number of switches and easily provides two outputs in antiphase. Therefore, it will be necessary to use two circuitries in quadrature, to provide four ways (figure 13). The transformer can easily boost the voltage from 12 V_{pp} to 50 V_{pp} as required. At these frequencies, the transformer dimensions will be small and its design will not be difficult. The switches are MOS transistors of IRF 520 type which have lower switching losses than bipolar transistors. Their particular advantage is their easier control.

(iii) *Adjustable power supply.*

The frequency is set by the ceramic characteristics. From a 12 V battery, the only way to control the motor speed is to adjust the square wave amplitude on each of the four ways. This can be achieved, for example, by controlling the 12 V power supply voltage. A step down chopper uses a bipolar transistor (TIP 42 C) which is controlled by an integrated circuit TDA 1060 dedicated to switching power supplies and can make the voltage vary from 0 to 95% of the value E .

5.3.2. Frequency control system. Two functioning types are available with this generator:

- (i) the frequency is adjusted by the command value at the input of the loop (manual mode);
- (ii) the motor works around its own resonance frequency (controlled mode).

The control system principle is based upon research of the maximum absorbed current which corresponds to the resonance frequency (figure 15(a)). However, variations of the resonance frequency may occur due to temperature (figure 15(c)) or load variations on the motor. So the frequency control system must assess the resonance frequency and follow its variations. An example of the research of resonance frequency is given in figure 15(a): the operating frequency must be increased when functioning point is A and must be decreased if it is B.

For every sampling time we need the sense of variation of the current amplitude ΔI_m , and the sense of variation of the frequency at the previous sample

$f'(N-1)$. So the sense of variation of the frequency at the present sampling time $f'(N)$ can be calculated.

The truth table (table 1) gives the four available possibilities summarized by the following equation:

$$f'(N) = \overline{f'(N-1)} + \Delta I_m.$$

It should be noted that this control system suits well ceramics which have a current peak symmetrical with respect to the maximum current (figure 15(a)). Under these conditions, the efficiency is the same for a given current if the functioning point is located at point A or B. But in the case of a ceramic with an asymmetrical peak (figure 15(b)), it is more difficult because a small variation of the frequency may lead to pulling the motor out of synchrony.

To calculate the sense of variation of frequency to maintain the functioning point at the resonance frequency, current amplitude variations are needed.

Measurement of average current values on a half-period is achieved directly on the DC supplies of the power amplifiers. It uses a shunt coupled to a low-noise differential amplifier (TL074) and an analogue filter which provides a voltage value V_F proportional to the average value I_m of the current amplitude. This value evolves slowly with time, so it is impossible to use a classic derivative circuit. At a given time, determination of the increase or decrease of $V_F = kI_m$ is sufficient. The following original way (figure 16) can achieve this perfectly.

At a given time t_1 , a clock H whose period is T (80 ms) driving a monostable, switches on K for a time t_c (15 ms). The capacitance C_3 is then being loaded under the voltage $kI_m(t_1)$ and holds this value even when K is switched off (during the time $T - t_c$). On the other input of the trigger IC2 (single supply 12 V), appears a voltage $kI_m(t_2)$. So the output voltage V_{S2} of the trigger gives the sign of $I_m(t_2) - I_m(t_1)$ and the sense of variation of the current is obtained. Values of ΔI_m and $f'(N-1)$ are sent to a two-exclusive-or gate driving a JK flip-flop.

Table 1. Truth table.

Operating point	ΔI_m	$f'(N-1)$	$f'(N)$
A	+	+	+
A	-	-	+
B	+	-	-
B	-	+	-

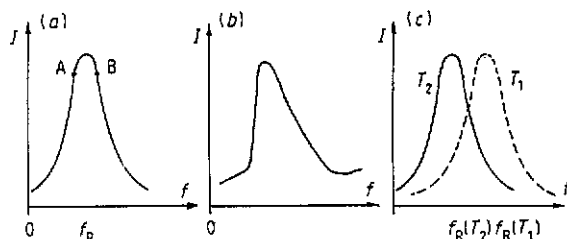


Figure 15. Output current I variations around the resonance frequency for a piezoelectric ceramic. Symmetrical (a) and asymmetrical (b) peak. (c) Influence of temperature.

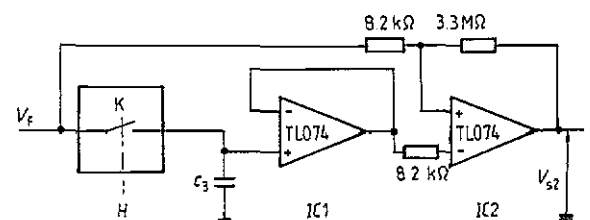


Figure 16. Determination of the sense of variation of the current amplitude.

This realizes the previous logical equation. The output Q of the JK corresponding to $f'(N)$ is connected to the exclusive-or for the next sampling time. The clock H drives the sampling of ΔI_m and $f'(N)$.

The output controls an integrator which provides an increasing or decreasing ramp according to the output Q . This ramp and an adjustable DC voltage which sets the centre frequency are added.

The resulting voltage drives the vco.

6. Experimental results

The load which has been used for the generator tests is a four-sector disc (diameter = 50 mm, thickness = 10 mm). The rotor comprises a metallic bearing pressed onto the cylindrical surface of the ceramic. The obtained motor is of a travelling wave ultrasonic motor type as described in section 3.3.2.

The equivalent scheme of the piezoceramic, which constitutes the load of the generator under test, clearly shows the proper capacitance C_0 of the ceramic, in parallel with the motional circuit (figure 17). The load can be approximated to a capacitance in parallel with a resistor around the serial resonance frequency of this branch.

The current i supplied by the generator is the sum of a sinusoidal current i_2 whose frequency is the resonance frequency and another current $i_1 = C_0 dv/dt$ whose amplitude depends on dv/dt , i.e. the form of the voltage supplied by the generator.

The experimental signals v and i for each of the three generators around the resonance frequency of branch 2 are given in figures 18–20.

It has been verified that the current supplied by the three electrical sources is sinusoidal when the frequency is near the resonance frequency of the motional branch.

For generators 2 and 3, $\pi/2$ spaced current peaks are superposed on the sinusoidal current.

The square wave output voltage of both generators yields an important dv/dt value when the voltage level switches and a current i_1 peak appears (figures 19 and 20); the duration of that peak depends on the inverting time of the polarities of the capacitance C_0 of the ceramic when voltage switching occurs. Because of the coupling, other peaks corresponding to the switching of the other channels appear at the same time, the voltage on the

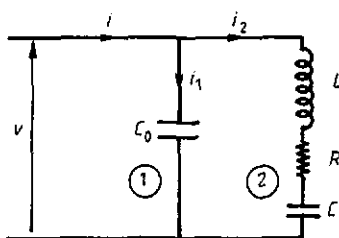


Figure 17. Electrical equivalent circuit of a ceramic near the serial frequency.

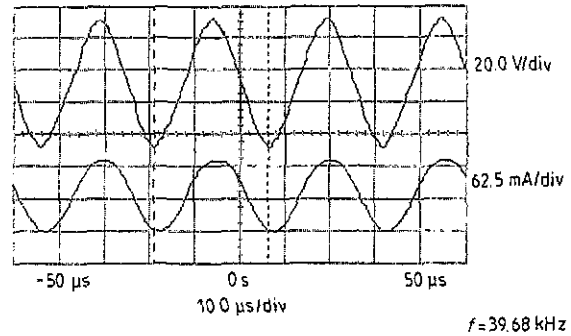


Figure 18. Generator 1. Experimental results of voltage and current output.

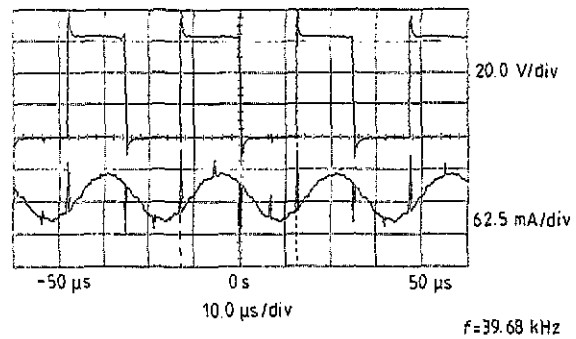


Figure 19. Generator 2. Experimental results of voltage and current output.

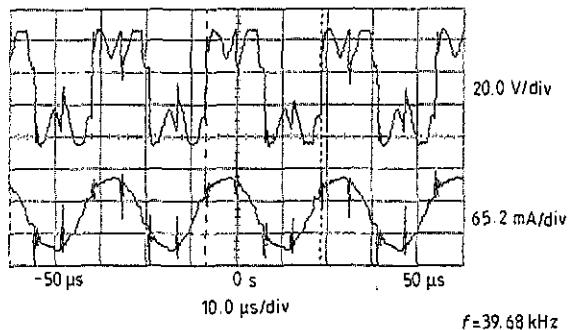


Figure 20. Generator 3. Experimental results of voltage and current output.

outputs being regularly $\pi/2$ dephased with respect to the observed channel. The waveform of the voltage v is differently affected by the supplied current.

- (i) Generator 1. Supplies a sinusoidal voltage; the current i will then be sinusoidal (figure 18) and does not show any peak.
- (ii) Generator 2. Two switches, one on each channel are capacitive half bridge mounted. The electrolytic capacitors which are used are of high value and give good voltage stability (figure 19). The power supply then works as a voltage source.

Table 2.

	Generator 1	Generator 2	Generator 3
Output signal	Sine	Square	Square
Output	Transformer	Switching power supply	Transformer
Maximum output level	50 V _{RMS} /1 A	200 V _{RMS} /1 A	50 V _{RMS} /0.15 A
Frequency range (kHz)	10–100	20–200	30–70
Phase shifting	Adjustable	Adjustable	Fixed
Number of channels	4 or 2	4	4 or 2

- (iii) Generator 3. Has a transformer which can be substituted by its equivalent scheme (resistance and self inductance). The self inductance slows down current variations and then lowers the peak amplitude by making the voltage source work as a current source.

In the power supply this effect has been emphasised by superimposing to the source another self inductance l of about 10 μH : the current peaks are then lowered but the voltage waveform is affected by the voltage drop in the self inductance $v_L = l \, di/dt$.

7. Conclusion

Table 2 summarizes the characteristics of the different generators.

- (i) Generator 1 is driven through a microprocessor, allowing each output to work in amplitude or phase independently.
- (ii) Generator 2 constitutes a motor to be driven in bursts and so obtain a step by step displacement for the positioning.
- (iii) Generator 3 is autonomous as it works with a 12 V battery. However, despite its reduced space

requirement, it suits many types of motor: it is not dedicated to a particular motor.

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